exploratorium®

The Exploratorium Teacher Institute and Institute for Inquiry Present

NGSS STEM Conference 2020

All Systems Go!

Investigating Earth Systems Science in All Science Classrooms

Earth's Energy Budget

The temperature of Earth hangs in the balance

Tools and Materials
Beans or other small counter – lots!
A friend or two who like to count

To Do and Notice
Put a pile of beans on one side that represents the sun. Clear an area that will represent Earth and another for space.

Scenario One – just in and out
How to play: In each round, the Sun gives 10 beans to the Earth, and the Earth keeps half of the beans and returns half of its total beans to space.

Here is what might happen in the first two rounds of play:

In round 1, the Sun gives the Earth 10 beans, and the Earth keeps 5 and returns 5 to space.
In round 2, the Sun gives the Earth 10 additional beans that combine with the 5 remaining from round 1 to result in 15 beans. The Earth returns half of these (7 or 8, your choice) to space, resulting in 7 or 8 total beans left on Earth.

Make a chart that keeps track of how many beans remain on Earth at the start and end of each round. Keep playing the game for several more rounds until you can predict what will happen next.

Round	Starting beans on Earth	Remaining beans on Earth
1	0	5
2	5	7
3	7	
4		
5		

Scenario Two – add an insulating layer

In Scenario Two, you will investigate the effects of having an atmosphere as an intermediate area between Earth and space. Make an additional space in front of you to represent the atmosphere.

How to play: In each round of Scenario Two, the Sun will still give 10 beans to the Earth, but now the Earth will send half of its total beans to the atmosphere, rather than directly to space. The atmosphere takes that total and divides it in two, sending half back to Earth and allowing half to go into space. For example, if the Earth starts with 10 beans and the Sun gives it 10 more, it would send 10 up to the atmosphere. The atmosphere returns 5 to Earth and lets 5 go into space. The final count on Earth for that round is 15 beans. You can start with the number of beans on Earth that remained after Scenario One.

Make a chart that keeps track of how many beans remain on earth at the end of each round. Keep playing the game for several more rounds until you can predict what will happen next.

Round	Starting beans on Earth	Remaining beans on Earth
1	10	15
2	15	
3		
4		
5		

What's Going On?

The Earth can be thought of as a physical system that has thermal energy radiating in from the Sun and thermal energy radiating back out into space. This game provides a simplified model of how energy flows in and out of the Earth until it reaches a steady-state equilibrium. In Scenario One, you may have noticed that if you continue to play additional rounds, you will reach a point where the Earth has 10 beans at the start of the round, receives 10 beans from the sun, and returns 10 beans to space. Since the number of beans entering and leaving the earth is the same, the total number of beans on Earth has reached a steady-state equilibrium point of 10. There is no reason to keep playing.

In Scenario Two, the atmosphere is added to the system, and this reduces the number of beans immediately returned to space. Steady-state is not reached until the Earth begins a round with 30 beans, receives 10 from the Sun, resulting in 40 beans total. It sends 20 to the atmosphere, which returns 10 to Earth and sends 10 to space, resulting in an equilibrium point on Earth of 30.

The beans represent the total amount of energy on Earth, which is directly related to its temperature. In this game, the amount of energy radiated back into space is based on a simple fraction of the amount of “energy” the Earth has, but in reality, it is governed by the much more complicated Stefan-Boltzmann Law, which states that the radiated energy is proportional to the temperature of the Earth to the fourth power. The math has been changed in this model for simplicity and is not meant to reflect the exact numerical values of energy transfer. The idea is to qualitatively show how the total amount of energy retained on Earth (and hence its equilibrium temperature) is impacted by changes in how much Energy is radiated back out into space.

Scenario Two shows that the presence of an insulating atmosphere increases the steady-state temperature of the Earth. It is estimated that if Earth didn’t have an atmosphere, its temperature would be -18°C, much too cold to support life as we know it. As our atmosphere changes, so will the steady-state temperature of the Earth. The amount of energy received from the Sun is essentially constant, but the increase in greenhouse gases in the Earth’s atmosphere has resulted in more energy radiated back towards Earth rather than out into space. While the energy exchanges on Earth are much more complex than this simple model, this game illustrates the fundamental idea that the temperature of the Earth is a direct result of its reaching a thermodynamic equilibrium. The Earth will continue to increase in temperature until the amount of energy radiated into space is equal to that which comes from the Sun.

Going Further

Scenario Three – what if the layer changes?

To see what happens if the atmosphere returns more beans to the earth, you can investigate a third scenario. In each round of Scenario Three, the sun will still give 10 beans to the Earth, and the Earth will send half of its total to the atmosphere. The atmosphere takes this total and now returns two-thirds of its beans to Earth and sends one third of the beans to space. You can start with the number of beans on Earth that remained after Scenario Two. What is the equilibrium number of beans on Earth with the atmosphere returning more beans? How would that alter the temperature of the Earth?

Another factor that impacts the energy the Earth receives from the sun is the Earth's albedo, or reflection coefficient. The albedo describes how much sunlight is reflected back from the earth (as opposed to re-radiated) by reflective bodies such as clouds and ice caps. To model the effects of albedo, you could create another scenario that imagines the energy from the sun being 12 beans a round, with 2 reflected off and don't even reach the earth. With a warming planet, the Earth's albedo is reducing, and this can be modeled by only reflecting 1 bean and allowing 11 to enter the Earth each round. How does this change the steady-state equilibrium point of the Earth?